REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	Oct. 1995	Final: 8/15/94-8/14/95

4. TITLE AND SUBTITLE
Bladed Disk Forced Response Augmentation For Research Training (AASERT)

5. FUNDING NUMBERS
AFOSR Grant
F49620-92-[redacted]
J- 0315

6. AUTHOR(S)
Sanford Fleeter

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)
Mechanical Engineering
Purdue University
West Lafayette, IN 47907

AFOSR-TR-96
0282

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Office of Scientific Research (NA)
Building 410
Department of the Air Force (AFSC)
Bolling Air Force Base, DC 20332
NA

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
92-J-0315

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

DISTRIBUTION CODE

19960617 125

13. ABSTRACT *(Maximum 200 words)*

Two AASERT students have actively participated in research in turbomachinery fluid dynamics and bladed disk forced response. The academic programs of the AASERT students were individually tailored. One AASERT student investigated nonlinear friction dampers for control of blade row aero-mechanics. The energy balance, harmonic balance, and time integration solution methods were applied to an unstable aero-mechanical model , thereby requiring a dry friction damper for stability. The results showed that the linearized harmonic and energy balance solutions can be used in preliminary design or as first guesses for nonlinear methods. The second AASERT student experimentally investigated the fundamental unsteady flow interaction phenomena significant to forced response and unsteady turbine heat transfer. The technical approach involved a series of experiments performed in a low speed research turbine. The rotor blade wake generated unsteady flow field, i.e., the unsteady forcing function, were measured over a range of turbine steady aerodynamic loading conditions. In addition, the unsteady heat transfer to the stator vane row was measured.

14. SUBJECT TERMS
Forced Response, Heat Transfer

15. NUMBER IF PAGES
11

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

FINAL REPORT FOR AASERT GRANT

BLADED DISK FORCED RESPONSE AUGMENTATION FOR RESEARCH TRAINING

(AFOSR GRANT F49620-92-J-0315)

INTRODUCTION

Bladed disk aerodynamically forced response is a universal problem. The primary mechanism of blade failure is fatigue caused by vibrations at levels exceeding material endurance limits. These vibrations occur when a periodic forcing function, with frequency equal to a natural blade resonant frequency, acts upon a blade row. Because a blade may have as many critical points of high stress as it has natural modes, the designer must determine which particular modes have the greatest potential for aerodynamic excitation. If a bladed disk forced vibration problem is detected early in the engine development process, the result is a delay in the development while a redesign is identified. If the problem is undetected until after deployment of the engine, then reliability problems that limit the engine's usefulness and dependability will be encountered.

Currently, every new gas turbine engine has had at least one blade row or stage with bladed disk forced response problems, with each engine company having at least one such problem and often more. This problem will be significantly increased in the next generation of gas turbine engines. Namely, to meet defense related aircraft propulsion needs into the next century, the DOD is pursuing aggressive improvements in turbine engine propulsion capability. These improvement goals, outlined by the IHPTET initiative, call for the doubling of propulsion engine capabilities by 2003. In response to this challenge, each DOD engine contractor has developed an Advanced Turbine Propulsion Plan which include detailed descriptions of the engine configurations needed to achieve the IHPTET goals along with the component technologies which must be developed. These plans show a number of recurring engine configuration features which add significant risk associated with bladed disk forced response.

Thus, the new technologies being developed to achieve higher thrust-to-weight ratios in advanced gas turbine engines also result in higher vibratory blade row responses and stresses which may delay engine development and cause long term durability problems

which adversely affect engine reliability. As a result, traditional methods of designing turbomachinery blading free from destructive levels of aerodynamically forced response will not meet the challenges presented by the next generation of engines, with developments in forced response technology required to assure the durability of future engines.

In particular, the design trend towards higher stage loading and higher specific flow are being attained through increased tip speeds, lower radius ratios, lower aspect ratios, and fewer stages. The resultant blade designs utilize thin, low aspect ratio blading with corresponding high steady state stresses. Also, the mechanical damping is considerably reduced in newer rotor designs, particularly those with integral blade-disk configurations (blisks) and in those without shrouds. These are similar trends in turbine blading, but they are further complicated by increased inlet and cooling temperatures that have resulted in thin-walled, complex cooling passage designs. As a result, advanced axial flow blade designs, both compressors and turbines, feature low aspect ratio blading which have significant unsteady flow induced vibration problems, both flutter and forced response. Additional mechanical damping must therefore be generated. One widely used technique for turbines is friction dampers. However, linear models are utilized to predict the resulting forced response. Thus, it is necessary to investigate nonlinear friction dampers for control of blade row aero-mechanics.

In addition, to improve the design capability for high temperature turbines, a thorough understanding of the turbine flow field and its effect on heat transfer, as well as forced response, is necessary. Of specific interest is the effect of unsteadiness on turbine heat transfer. Fundamental unsteady aerodynamic data have shown that there is a very strong interaction between the steady and unsteady flow fields on high camber airfoil surfaces such as turbine blades. Also, the particular phenomena generating the unsteady flow has a significant effect on the resulting blade surface unsteady aerodynamics. However, current turbine heat transfer experiments have not considered these fundamental flow phenomena. Rather these experiments have been concerned with more "design type" results. For example the effect of wakes on unsteady heat transfer has been considered, with the wakes not characterized, other than perhaps by the wake velocity deficit. However, data have clearly demonstrated that the wake deficit is not sufficient to define the driving unsteady flow phenomena, i.e., the blade wakes. Thus, there is clearly a need for fundamental level unsteady heat transfer experiments which consider the basic unsteady flow phenomena which drive unsteady heat transfer as well as forced response.

AASERT THESIS RESEARCH & CURRENT STATUS

Two AASERT graduate students have actively participated in thesis research in the area of turbomachinery fluid dynamics and bladed disk aerodynamically forced response, thereby supporting the DOD's IHPTET initiative. The academic programs of the AASERT students have been individually tailored to meet their needs based on their particular educational backgrounds. Their thesis research, being performed under the direction of Professor Sanford Fleeter, has been an important part of the AFOSR sponsored research program: "Aero-Thermodynamic Distortion Induced Structural Dynamic Response of Multistage Turbomachinery Blading," Program Manager Major Dan Fant.

Nonlinear Friction Dampers For Control Of Blade Row Aero-Mechanics

The research of one AASERT student is directed at investigating nonlinear friction dampers for control of blade row aero-mechanics. In particular, turbomachine designs which meet increased performance requirements have been accomplished with blading which is very near to aero-mechanic stability limits. For example, turbines are inherently unstable, with friction dampers, i.e., shrouds, used to provide the necessary additional mechanical damping required for stability.

Currently, linearized friction damper models are used to predict these stability limits. However, during engine development, these linearized solutions are often found to be inadequate. Thus, for accurate blade row stability predictions, the nonlinear effects of friction dampers must be considered. This is being accomplished herein by developing a coupled aero-mechanics model which considers nonlinear friction dampers.

The steady-state system response, i.e. the vibration level at which the system will continue to vibrate over time, must satisfy the equations of motion, and the net energy must remain constant from one cycle to the next. These requirements lead directly to using either an harmonic balance technique, an energy balance or a time integration method to find the system-steady state response.

The harmonic balance method is the most widely used technique in industry to determine the steady-state response of a forced system. It uses the equations of motion but requires that all nonlinearities be linearized. Simple harmonic motion is then assumed and the linearized ODE's become a set of nonlinear equations. Note that unlike both the energy balance and time integration methods, the harmonic balance method cannot be used to solve a non-linear or non-harmonic set of equations. Therefore, an explicit harmonic

approximation for every force in the system is necessary before this method can be applied, with simple harmonic motion then assumed.

The energy balance method states that for steady state vibration, the net energy change per cycle of vibration must be zero. If the net energy change per cycle of vibration is positive, the amplitude of vibration will increase. Similarly, negative net energy changes cause the amplitude to decrease. Therefore, the amplitude of vibration can be varied to find the amplitude for which the net energy change is zero.

The time integration method uses the nonlinear coupled ordinary differential equations of motion and integrates them through time from an initial condition until either a steady state, a repeated cycle, or a divergence is obtained. In general, time integration methods can be used to determine the steady-state solution to a set of nonlinear differential equations by starting at an arbitrary initial condition and integrating through time. As long as the initial conditions are chosen in a stable region, this method should find a steady state or limit cycle solution. Major benefits of this solution technique include using the actual equations of motion (not assuming a modeshape of vibration) as well as the ability to utilize more accurate nonlinear friction dampers and to be expanded to include nonlinear aerodynamic and forced response force descriptions. The major drawback is the large computational time required for large DOF systems.

Time integration methods should yield the most accurate solutions by allowing the physical model to determine the modeshape and amplitude of the vibratory response. This may seem like a slight improvement since the energy and harmonic balance methods use the first harmonics of the response as the assumed modeshape. However, the energy balance method integrates each force through this assumed modeshape to determine the amplitude of the response, thus compounding the errors of any harmonic motion approximation. Similarly the harmonic balance method requires all non-harmonic forces to be explicitly harmonically approximated before any analysis. Note that when the harmonic balance method can be applied and trusted to give accurate solutions (where a single harmonic description of the non-linearity is adequate), it is by far the most computationally efficient method for obtaining steady-state solutions to nonlinear dynamic problems. However, every nonlinear force must be approximated and therefore, the harmonic balance solution is only as good as these approximations. For highly nonlinear forces, the harmonic approximations can be extremely poor.

This research is concerned with the effect of nonlinear mechanical damping, i.e., nonlinear friction dampers, on blade aerodynamically forced response. Thus, the energy balance, harmonic balance, and time integration, solution methods are applied to an aero-mechanical model including only a mass, spring, viscous damper, and dry friction damper. The aerodynamic and structural restoring forces are assumed to be linear. Therefore, they are lumped together into single spring and viscous damper constraints. Since the entire aero-mechanical system is linear except for the friction damper, the effects of using different damper stiffness ratios and the nonlinear effects of the friction damper are isolated from all other nonlinearities. To simulate an aerodynamically unstable blade row, the viscous damper coefficient, the system damping excluding the friction damper, must be negative. Thus, a friction damper is required to stabilize the blade row.

Both the steady state vibration level (stable limit cycle) and the stability limit (unstable limit cycle) are important design/optimization considerations. The steady state vibration is a level of constant vibration which the turbomachine blade row will endure until the operating conditions are changed. This steady state vibration level directly translates to a continuous level of vibratory stress. Similarly, the stability limit is the maximum vibration level at which the system will stabilize. Any transient that forces the system to transition into a vibration level above the stability limit will cause the system to go unstable. This is a limitation and concern for aerodynamically unstable friction damped system. However it is an improvement over the totally unstable undamped system.

The energy balance, harmonic balance, and time integration solution techniques agree on the qualitative effects that friction dampers have on the response of an aerodynamically unstable blade row. The linearized methods also agree well quantitatively with the nonlinear time integration predictions for low levels of damper stiffness ratio. At higher levels of stiffness ratio and higher levels of instability where the damper and therefore it's nonlinearities have larger effects, the linearized methods tend to diverge from the nonlinear time integration method. Since the two linearized methods linearize the problem in different ways, the fact that both diverge from the nonlinear solution and each other in this region is strong evidence that the differences are due to the linearizations and solution methods.

The linearized methods, harmonic and energy balance, are good first guesses near the stability boundaries and are sufficient for conditions away from critical stability regions. The linearized solutions diverge near the stability limits due to the differences in the linearization and solution methods. The friction damper nonlinearity is relatively small. If

more nonlinearities were included, or the nonlinearity being linearized were more severe, i.e. non-linear aerodynamic forces, or a non-linear forcing function, this linearization divergence could be worse.

The linearized solutions can be used in preliminary design stages or as first guesses for nonlinear methods. The linearized methods work well for systems where the nonlinearities are small, or if accuracy is not as important as trends. In final design or for safety and optimization purposes, a more rigorous nonlinear analysis or extensive testing is needed for quality assurance, i.e. safety, and cost/weight optimization.

Unsteady Flow Phenomena Driving Forced Response & Unsteady Heat Transfer

The second AASERT student is experimentally investigated the fundamental unsteady flow interaction phenomena which are significant with regard to forced response and unsteady turbine heat transfer. The technical approach involves a series of experiments performed in a low speed research turbine. The rotor blade wake generated unsteady flow field, i.e., the unsteady forcing function, is to be measured over a range of turbine steady aerodynamic loading conditions. In addition, the unsteady heat transfer to the stator vane row is to be measured.

The Purdue Low-Speed Research Turbine is a 2,500 rpm two-stage axial-flow turbine with constant hub and tip diameter, Figure 1, and 50% reaction NACA A_3K_7 series airfoils. Air at ambient pressure and temperature is drawn into the turbine inlet by a centrifugal blower powered by a 100-hp electric motor. Air flow rates of 3,000–5,400 cfm are measured by a 20-in. diameter venturi flow meter and regulated by a variable inlet vane damper, enabling the turbine flow coefficient to be varied from 0.3 to 0.5. Turbine loading is controlled by a water brake dynamometer which dissipates 40 hp at the highest turbine loading, enabling the turbine stage loading coefficient to be varied from 0.4 to 1.8.

Signals from instrumentation in the rotating frame of reference are transmitted through a 46-channel mercury-wetted slip ring. Thermocouple and rotational speed measurements are taken with 16-bit resolution data acquisition boards, with all other data sampled with 12-bit resolution high-speed data acquisition boards at approximately 20 kHz sampling rate, approximately 15 times blade pass frequency, after passing through a low-pass filter with a cut-off frequency of 10 kHz.

Periodic signals are ensemble or phase-locked averaged over at least 200 rotor revolutions. The signals are then digitally Fourier transformed. For signals acquired in the rotating frame of reference, the Fourier transform operates with respect to the time domain to decompose the signal into temporal harmonics. The zeroth (time mean) and vane pass frequency harmonic are obtained for analysis. Frequency leakage associated with digital Fourier transforms is avoided by sampling data in the time of exactly one rotor revolution. Aliasing is avoided by sampling at a frequency well exceeding the Nyquist frequency and bandwidth limiting the signals with low-pass analog filters.

Unsteady pressure signals acquired in the stationary frame of reference are digitally Fourier transformed with respect to time and with respect to space. Pressure data acquired at four equally-spaced circumferential locations around the turbine case are used to measure the blade difference mode. For the potential field interactions, a 2-lobe blade difference mode is predicted at rotor-1 blade pass frequency. At station 4, a 4-lobe blade difference mode is predicted at rotor-2 blade pass frequency.

A series of experiments are being performed in the extensively instrumented research turbine directed at investigating the effect of blade row interaction on the forcing function to a rotor blade row as well as the resulting rotor blade unsteady aerodynamic blade loading and heat transfer. Steady and unsteady data are being acquired and analyzed to investigate the effects of flow unsteadiness due to rotor/stator interaction on the rotor blades through measurement of the unsteady forcing function (gust), steady response (stage efficiency), and unsteady response (blade loading, heat transfer). Data being acquired and analyzed include the following. (1) Forcing Function - The steady and unsteady three-dimensional velocity and static pressure in the rotor inlet and exit flow fields are measured in the rotating frame of reference. Additionally, in the stationary frame of reference, spanwise surveys of the rotor inlet and exit flow fields are made at four equally-spaced, circumferential locations, thereby quantifying the forcing function. (2) Blade Row Unsteady Aerodynamic Response - The steady and unsteady blade surface pressures along the midspan suction and pressure surfaces and along a spanwise locus at one chordwise location of the suction surface are measured. (3) Blade Row Unsteady Heat Transfer Response - The steady and unsteady blade surface heat transfer along the midspan suction surface and along a spanwise locus at one chordwise location of the suction surface are measured.

Determination of the forcing function to the rotor blades requires the measurement of the gust static pressure and velocity in the rotating frame of reference. Additionally, gust

static pressure measurement in the stationary frame of reference is required. Because the unsteady flow field is highly three-dimensional, spanwise forcing-function measurements are made.

Gust Static Pressure and Velocity

Unsteady static pressure measurements of the gust are made using a pressure probe designed at Purdue and constructed with a Kulite miniature pressure transducer. The probe is calibrated in a jet of known velocity and flow angle to determine its sensitivity to yaw and pitch angles and velocity magnitude. Steady calibration of pressure versus transducer voltage is made with a water manometer and pressure chamber. Unsteady calibration to determine any natural frequencies of the probe is made with a resonance tube at frequencies as high as four times blade pass frequency.

Three-dimensional velocity measurements of the gust forcing function are made with a three-wire hot-wire probe. The probe is calibrated in a jet for sensitivity to pitch and yaw angle and velocity magnitude. Once voltage versus pitch angle, yaw angle, and velocity magnitude is known for each hot-wire, a combination of Jorgensen's and King's cooling laws are used with a variable transformation which mathematically separates the dependence of flow angle and velocity magnitude.

Blade Row Response

The resulting downstream rotor response to the gust forcing function consists of unsteady blade loading (surface pressure) and heat transfer data acquired in the rotating reference frame.

Rotor blade loading measurements are made using three blades instrumented with Kulite miniature pressure transducers at twenty locations on the blade pressure and suction surfaces. Unsteady calibration to determine natural frequencies of the probe and to account for signal attenuation and phase shift due to passage effects is made with a speaker-driven resonance tube at pressure signal frequencies as high as five times blade pass frequency.

Rotor blade heat transfer measurements are made with a heated rotor blade instrumented with heat gages. The aluminum rotor blade features a pocket in which is mounted thin, etched-foil heaters. Each heater is 0.004-in. thick, Kapton insulated, and rated at 10 W/in^2 at 28 V DC. Blade temperature is maintained by the heaters with a temperature control circuit using a feedback thermistor mounted in the blade. Thin -film

heat gages are mounted flush to the blade at nine locations on the suction surface. Heat-gage sensor temperatures are determined using a constant-current anemometer circuit.

Separate analytical models are used to determine steady and unsteady blade heat transfer based the linearity of the governing equations. The steady heat transfer coefficient H is given implicitly by

$$\frac{T_{HG} - T_A}{T_\infty - T_A} = \frac{2}{r_o} \sum_{n=1}^{\infty} \frac{\tanh \lambda_n L}{\frac{\lambda_n k_Q}{H} + \tanh \lambda_n L} \frac{\frac{1}{\ell}\int_0^{\ell} J_0(\lambda_n r)\,dr}{\lambda_n J_1(\lambda_n r_o)} \tag{1}$$

$$J_0(\lambda_n r_o) = 0 \tag{2}$$

where the steady temperature measured by the heat gage is T_{HG}, T_A is the steady airfoil temperature at the heat-gage location measured by the local thermocouple, T_∞ is the steady, air stagnation temperature at the midspan stator inlet measured by the stagnation temperature probe, L is the heat-gage height, r_o the heat-gage radius, ℓ the hot-film half-length, k_Q the thermal conductivity of the fused quartz substrate of the heat gage and the eigenvalues λ_n are given implicitly by Equation 2.

Once the steady heat transfer coefficient is determined, it is nondimensionalized by forming the Nusselt number.

$$\overline{Nu} = \frac{H L_{SS}}{k_f} \tag{3}$$

where L_{SS} is the blade suction surface midspan arclength, and k_f is the thermal conductivity of air evaluated at temperature $T_f = \frac{1}{2}(T_A + T_\infty)$.

For the unsteady heat transfer model, only the presence of the platinum film may be ignored, the alumina coating must be included in the analytical model. The unsteady heat transfer coefficient h_1 (first harmonic) is given by

$$h_1 = \frac{-\tau_{HG1}}{(T_{HG} - T_\infty)}\left[(H + \kappa\mu)\cosh(\zeta a) + (\kappa H + \mu)\sinh(\zeta a)\right] \tag{4}$$

$$\zeta = \sqrt{\frac{i\omega}{\alpha_C}} \tag{5}$$

$$\mu = \sqrt{\left(k\rho c_p\right)_C} \tag{6}$$

$$\kappa = \sqrt{\frac{\left(k\rho c_p\right)_Q}{\left(k\rho c_p\right)_C}} \tag{7}$$

where a is the alumina coating thickness, τ_{HG1} is the first harmonic perturbation temperature measured by the heat gage, k, ρ, c_p, and α represent the thermal conductivity, density, specific heat, and thermal diffusivity of the fused quartz substrate (subscript Q) or the alumina coating (subscript C) of the heat gage.

With the unsteady heat transfer coefficient determined, it is nondimensionalized by forming the Nusselt number,

$$Nu_1 = \frac{h_1 L_{SS}}{k_f} \tag{8}$$

The platinum film sensor of the heat gage and local thermocouples are used to measure temperature. The blade-mounted heat gage is calibrated *in situ* by varying the set-point temperature of the blade heater controller. Because the convection heat transfer of the blade in quiescent air is so small, the temperature of the platinum film is nearly the same as the blade metal temperature measured by the thermocouple adjacent to the heat gage. Once the blade steady-state temperature has been reached, using the constant-current anemometer circuit, the resistance of the platinum film of the heat gage is measured along with the temperature of the local thermocouple to obtain platinum film electrical resistance versus temperature . Prior to installation into the blade, by using a precision thermistor reference, the thermocouples are calibrated in a heated air jet.

The experimental determination of the thermophysical properties of the heat-gage substrate are made using a technique based on the time response of the heat gage to a step change in the electric current flowing through the platinum film. From this technique values of k, ρ, and c_p of the fused quartz substrate are found. Using tabulated values for the alumina coating properties introduces very small uncertainty into the determination of

unsteady heat transfer, because of the model's slight sensitivity to the coating properties; further, the effect of the coating on steady heat transfer is negligible.

Rotor blade heat transfer is correlated against the Reynolds number.

$$Re = \frac{Q_{rel\ rin} L_{SS}}{\nu_{rin}} \tag{9}$$